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Original Article

Late quaternary paleoseismology of the Khlong Marui Fault in the Thub Pud area, Phang Nga, southern Thailand

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Abstract

Remote sensing and aerial photography techniques have been applied in a study of the Khlong Marui Fault in Surat Thani and Phang Nga provinces of southern Thailand. Several faults are recognized in the region, trending mainly NE–SW. The common geomorphological features associated with the Khlong Marui Fault include fault scarps, triangular facets, offset streams, shutter ridges, hot springs, and linear valleys. Paleoseismological trenching at Ban Pak Dan across the NE–SW Khao Panom segment of the Khlong Marui Fault was conducted to identify and date faulting events. Two events with magnitude (Mw) 6.9 were observed at the Ban Pak Dan trench site, and OSL dating indicate late Quaternary faulting events from 20,000 ±1,500 years ago; and from 14,500 ±1,000 years ago. The maximum slip rate is estimated to be 0.25–0.50 mm/yr, and the recurrence interval of seismic events is between 1,000 and 2,000 years.

Keywords: Khlong Marui Fault, quaternary fault, paleoseismology, seismicity, southern Thailand

1. Introduction

After the Mw 9.1 Great Sumatra earthquake on 26 December 2004 (Satake, 2006), a devastating tsunami impacted the Andaman Sea and nearby coastal regions including the west coast of southern peninsular Thailand. Moreover, southern Thailand has experienced many micro-earthquakes and some moderate earthquakes (Thai Meteorological Department [TMD], 2021). Several micro-to-moderate earthquakes have been located along major fault traces in southern Thailand, including the Ranong and the Khlong Marui Faults. The largest known earthquake, with Mw 5.0, occurred on the northeastern portion of the Ranong Fault on 8 October 2006 (United States Geological Survey [USGS], 2006), and it is thought to be a delayed response to the 2004 great Sumatra earthquake (Searle & Morley, 2011; Tingay *et al*., 2010). It is strongly suggested that the Ranong and Khlong Marui Faults are active based on seismological and paleoseismological data from prior studies (Charusiri *et al*., 2007; Department of Mineral Resources [DMR], 2007; Keawmaungmoon, 2010; Noppradit, 2013; Pananont *et al*., 2010; Royal Irrigation Department [RID], 2009; Thipyopass, 2010; The Malaysia-Thailand Working Group, 2018). Thus, southern Thailand may in the future have significant moderate to large earthquakes. In order to mitigate the impact of earthquakes, seismic hazard zonation is desired. However, paleoseismological data of the Khlong Marui Fault are still insufficient for detailed seismic hazard assessment. Thus, we selected the Khlong Marui Fault for this research (the location is shown in Figure 1). The main objectives were to (1) identify

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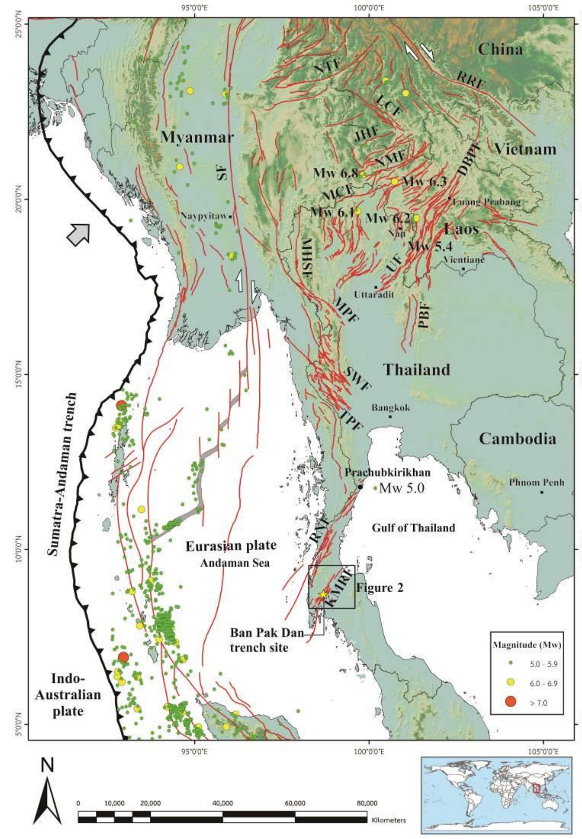

Figure 1. Map of SE Asia showing major active faults (modified from Wiwegwin *et al*., (2020)) and epicenters of moderate to strong earthquakes (Mw>5.0). Note: yellow star, Ban Pak Dan trench site; NTF, Nanting He Fault; LCF, Lancang Fault; JHF, Jinghong Fault; NMF; Namma Fault; MCF, Mae Chan Fault; RRF, Red River Fault; UF, Uttaradit Fault; DBPF, Dien Bien Phu Fault; SF, Sagaing Fault; MPF, Mae Ping Fault; PBF, Phetchabun Fault; SWF, Srisawat Fault; TPF, Three Pagoda Fault; MHSF, Mae Hong Son Fault; RNF, Ranong Fault; and KMRF, Khlong Marui Fault

and characterize geomorphological features resulting from recent fault movement, (2) determine the number of paleoseismological events, and (3) estimate slip rate and recurrence interval of the Khlong Marui Fault. We applied optically stimulated luminescence (OSL) dating to determine the depositional ages of sediment layers involved in paleoseismological events.

2. Neotectonics and Seismicity in Southern Thailand

The neotectonics of Thailand are generally related to progressive NNE movement of the Indo-Australian plate and collision with the Eurasian plate, see Figure 1 (Charusiri *et al*., 2007; Peltzer & Tapponnier, 1988). Penetration of the Indo-Australian plate into the Eurasian plate started in late Paleogene (Packham, 1996). Localized dextral shears observed in migmatites in southern Thailand indicate movement on the NE-SW trending Ranong Fault during late Paleocene to early Eocene (Morley, Charusiri, & Watkinson, 2011; Watkinson *et al*., 2011). In the Middle Eocene, the NW-SE trending Mae Ping and Three Pagoda Faults had sinistral shear motion in northern Thailand, as a result of India-Burma coupling in advance of the collision of Indo-Australian and Eurasian plates. To the south, there was a major period of dextral shear along the NE-SW trending Ranong and Khlong Marui Faults (Kanjanapayont, Klötzli, Thöni, Grasemann, & Edwards, 2012; Watkinson *et al*., 2011).

After late Eocene (~40 Ma), the regional compressive stress in this region changed to N-S due to the Indo-Australian plate moving continuously north (Charusiri *et al*., 2002). This also resulted in a reversal in the sense of movement along the NW-SE trending Mae Ping and Three Pagoda Faults during Oligocene to early Miocene (~23 Ma) (Lacassin *et al*., 1997), when slip sense of these faults changed to right-lateral, and the Ranong and Khlong Marui Faults were possibly reactivated as sinistral faults in the late Eocene to early Oligocene (30 and 37 Ma), synchronously with E-W extension onshore and offshore of Thailand (Hall & Morley, 2004; Nachtergaele *et al*., 2019; Polachan *et al*., 1991).

Presently, the collision of the Indo-Australian and Eurasian plates is ongoing; this collision causes the continuous evolution of structure in the SE Asia (Watkinson, Elders, & Hall, 2008), and generates the fault kinematics of a complex fault system (Shi *et al*., 2018). Moreover, this collision generates movements in active faults and seismicity in the region. The present-day seismicity in southern Thailand is also characterized as either low (Morley *et al*., 2011; Palasri & Ruangrassamee, 2010), or very high (Pailoplee, 2014; Pailoplee & Charusiri, 2016; Pailoplee, Sugiyama, & Charusiri, 2010; Sutiwanich, Hanpattanapanich, Pailoplee, & Charusiri, 2012), and is possibly related to the Ranong and the Khlong Marui Faults. Approximately 104 earthquake events have been reported nearby and within southern Thailand (TMD, 2021). Two earthquakes with ML 5.3 occurred in the Andaman Sea, to the south of Phuket island, on 16 July 2013 and 27 October 2014. The largest known earthquake with its epicenter close to the mainland of southern Thailand, with a magnitude of ML 5.0 (or Mw 5.0 as reported by USGS (2006)), occurred on the northeastern portion of the Ranong Fault on 8 October 2006 (TMD, 2006). The epicenter was to the east of Prachubkirikhan downtown (Figure 1) where minor damage was reported from this event. On 6 May 2015, an ML 4.6 earthquake and its aftershocks occurred in the Andaman Sea to the east of Phuket Island. This earthquake was inferred to be generated by the movement on the southwestern segment of the Khlong Marui Fault. Minor damage was reported from this event, particularly in the Thalang area of the island. In 2007, an increase in the number of local earthquakes along the Khlong Marui Fault was detected in the middle portion of the fault, indicating the activation of the Khlong Marui Fault after the Mw 9.1 Great Sumatra earthquake (Bhongsuwan, Pispak, & Dürrast, 2011; Pispak, Dürrast, & Bhongsuwan, 2010).

3. Lineaments and Fault Segments of the Khlong Marui Fault

Landsat 7 images and DEMs obtained from Shuttle Radar Topography Mission (SRTM) covering the Surat Thani and Phang Nga provincial areas have been interpreted to identify lineaments and Quaternary faults. Lineaments were recognized based on morphological features, their correlation with tectonic elements, and available geological maps. There are 2,543 lineaments which strike mainly NE–SW, with minor conjugate lineaments trending NW–SE (Figure 2).

The Khlong Marui Fault is well defined, and is visible as a sharp lineament in aerial photographs, DEMs, and satellite images. The Khlong Marui Fault strikes NE–SW and shows left-lateral strike-slip movement. The Khlong Marui Fault has a total length of *ca*. 150 km, which can be divided into 50 major segments based on fault geometries and orientations, associations with geomorphological features, and their seismicity history (Figure 2). The length of these fault segments ranges from 2 to 68 km. Fault traces are clearly visible along the boundaries between the pre-Cenozoic rocks and unconsolidated Quaternary sediments (all showing clear traces of Quaternary faulting).

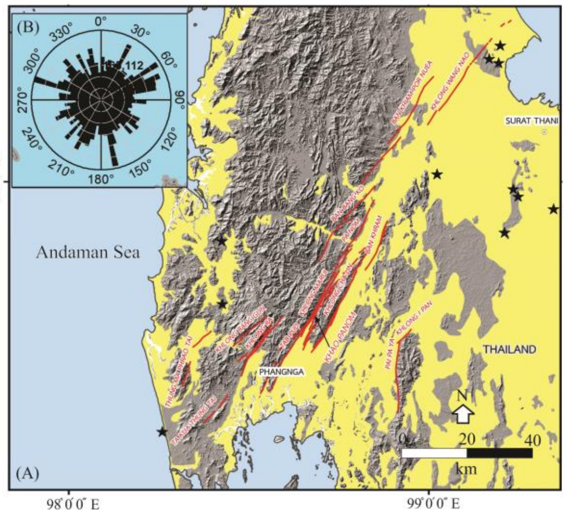

Figure 2. Map showing the 150 km-long, NE-trending Khlong Marui Fault and its 50 major fault segments based on fault geometries and orientations, associations with geo morphological features, and their seismicity history. Principle orientations of lineaments are shown as a rose diagram (B, inset in A), The names and locations of individual segments of the Khlong Marui Fault are also displayed (A). Black stars represent hot spring locations, and the yellow area indicates Cenozoic sediments in Surat Thani and Phang Nga.

4. Geomorphology of the Khlong Marui Fault

Based on remote sensing interpretation and a field survey, geomorphological features of the Khlong Marui Fault include fault scarps, triangular facets, offset streams, shutter ridges, linear valleys, hot springs, and linear mountain fronts (Figure 3). Further to the northeast of the Ban Pak Dan trench site, a northwestward-flowing stream channel shows a sinistral offset of 50-200 m; and to the southwest of our trench site, a stream channel also shows a sinistral offset of *ca*. 400 m. (the stream flows southwestward along the fault trace before returning to its northwestward course; Figure 3). These offset streams indicate left-lateral strike-slip along the Khao Panom segment. NE to NNE–trending shutter ridges parallel to the mountain front are found to the west of Ban Pak Dan. A series of triangular facets is present in the Ban Pak Dan area on escarpments that face SE and NW (Figure 4). Based on geomorphological features observed in this area, it is possible that the Khao Panom segment of the Khlong Marui Fault has produced both vertical and lateral movements. These geomorphological features were used to select the location of the trench site at Ban Pak Dan.

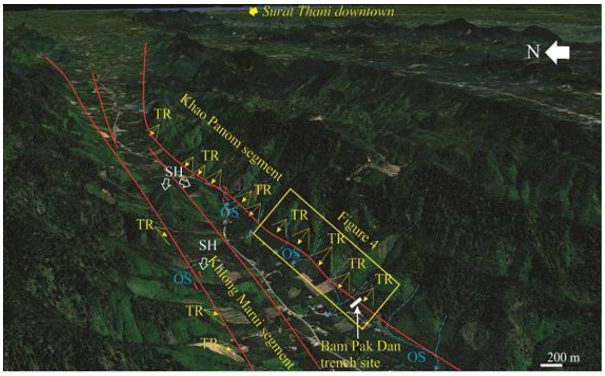

Figure 3. Geomorphologic features on the Khlong Marui Fault interpreted from remote sensing in the study area include triangular facets, offset streams, shutter ridges, linear valleys, and linear mountain fronts. Note: offset stream (OS), triangular facets (TR), and shutter ridge (SH). The displacement of the offset stream observed along the Khao Panom segment is *ca*. 50-400 m indicating a sinistral movement. A white box represents a Ban Pak Dan trench site.

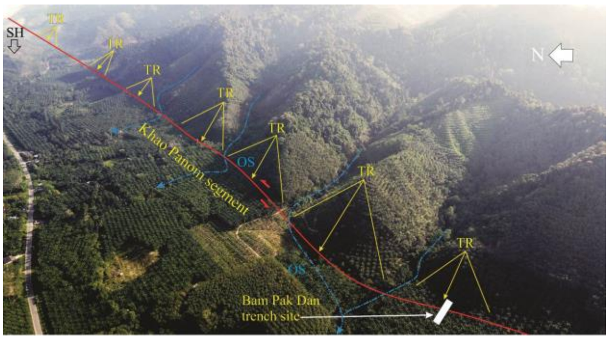

Figure 4. A bird's eye view from drone showing triangular facets (TR) and offset streams (OS) along the Khao Panom segment of the Khlong Marui Fault in the Ban Pak Dan area; a series of triangular facets is present on the escarpment that faces NW. The Ban Pak Dan trench site is carefully chosen for paleoseismic study based on triangular facets and offset streams.

5. Paleoseismological Events from Trenching Data

We trenched across the NE–SW Khao Panom segment of the Khlong Marui Fault at Ban Pak Dan (see location in Figure 4; latitude 8° 37.222'N and longitude 98° 40.883'E). The south wall is shown in this paper, and the stratigraphy of the trench wall can be separated into eight unconsolidated units; A to H, based on their sedimentological characteristics. Details of the individual units are described in Table 1 and Figure 5.

Table 1. Description of Quaternary sediments units in the Ban Pak Dan trench, Thub Pud, Phang Nga, southern Thailand

NO.	Sediment unit	Description	Depositional environment
1	A	Unit A is a clast-supported colluvial unit characterized by gravel (pebble to boulder), sand, silt and clay. Most clasts in the unit are subangular to rounded, and consist of sandstone, siltstone, mudstone, and quartz. The unit is poorly to moderately sorted. This unit is cut by the fault.	Gravity transport
2	B	Unit B is an alluvial unit composed of greyish brown sand, silt, clay with cobbles.	Gravity transport
3	C	Unit C is a clast-supported colluvial unit characterized by gravel (pebble to boulder), sand, silt and clay. Most clasts in the unit are subangular to rounded, and consist of sandstone, siltstone, mudstone, and quartz. The unit is poorly to moderately sorted. This unit is cut by the fault.	Gravity transport
4	D	Unit D is an alluvial/colluvial unit consisting of gravel, sand, silt, and clay. This unit is clast-supported gravel unit. The gravels consist mainly of subangular to angular clasts of quartz, sandstone, siltstone, mudstone. Gravel size varies from granule to cobble. The unit is moderately to well sorted.	Debris flow
5	E	Unit E is an alluvial unit consisting of greyish brown sand, silt, clay, with gavel (granule and pebble).	Debris flow
6	F	Unit F is an alluvial/colluvial unit consisting of gravel, sand, silt, and clay. This unit is a clast-supported gravel unit. The gravel consists of subangular to angular clasts of quartz, sandstone, siltstone, mudstone. Gravel size varies from granule to cobble. The unit is moderately to well sorted.	Debris flows and gravity transport
7	G	Unit G is an alluvial unit consisting of reddish-brown sand, silt, clay, with gavel (granule and pebble).	Debris flows and gravity transport
8	H	The youngest units, which is the topmost soil layer; it consists of silt, and clay with some gravel and sand.	Debris flows and gravity transport

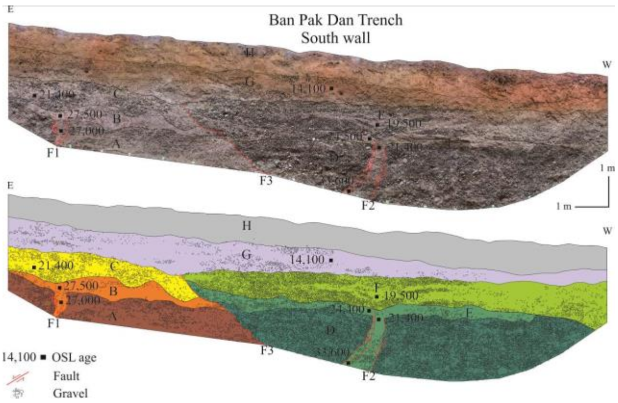

Figure 5. Stratigraphy and ages of Quaternary sediments along the south wall of the Ban Pak Dan trench. Faults identified in the trench wall are F1, F2 and F3. Black square boxes indicate sample locations with OSL ages. The location of the trench is shown in Figures 3 and 4. Unit A: colluvial sediments; Unit B: alluvial sediments; Unit C: colluvial sediments; Unit D: alluvial/colluvial sediments; Unit E: alluvial sediments; Unit F: alluvial/colluvial sediments; Unit G: alluvial; and Unit H: top soil.

The sediments of units A–C were mainly deposited by gravity transport at the base of the hill slope at Ban Pak Dan site, while the sediments of units D–E were mainly deposited by debris flow in the area nearby Ban Pak Dan site. Units F–H were deposited by debris flows and gravity transport. At least two faulting events have been identified at the Ban Pak Dan trench site (Figures 5 and 6); the faults strike 175°–188° and dip 50º–64º to NW. The fault traces cut units A–E, and terminate in the lower part of unit G. The first faulting event (F1 and F2) cut alluvial/colluvial sediment units in the lower part of the trench (units A, B, D and E), and formed a wedge-shaped colluvial deposit after strong ground shaking. Vertical and lateral offsets of sediments in the trench were possibly generated; vertical component was measured as 0.5 m. After deposition of unit F, movement of the second faulting event (F3) caused displacement of units A, B, C, D, E and F, and created the sharp vertical contact between these six units. It is interpreted that movement of the second event was principally lateral (strike-slip). An offset defined by the shift of a channel suggests a sinistral movement on the fault. We sampled sands from units A-G for Optically Stimulated Luminescence (OSL) dating with application of Single Aliquot Regeneration techniques (SAR) for constraining the timing of faulting. Equivalent dose measurements of OSL dating were made using an OSL instrument (Model Lexsygsmart-Automated TL/OSL Reader, Germany) at the Thailand Institute of Nuclear Technology (TINT). For the annual dose, the concentrations of U, Th, K and Rb were also analyzed using a HPGe Gamma Spectrometer at TINT. The OSL ages are summarized in Table 2. Based on OSL ages, we interpreted that the first paleoseismological event in this trench might have occurred at 20,000 ±1,500 years ago, and the second event occurred at 14,500±1,000 years ago (Figure 6). The paleomagnitude estimation is based on the equation of Wells and Coppersmith (1994) as follows:

$$Mw = 5.08 + 1.16 \log (SRL) \qquad (1)$$

where SRL is the surface rupture length determined from length of the Khao Panom segment (38 km). Using Equation (1), the paleomagnitude generated by movement on the Khao Panom segment could be Mw 6.9.

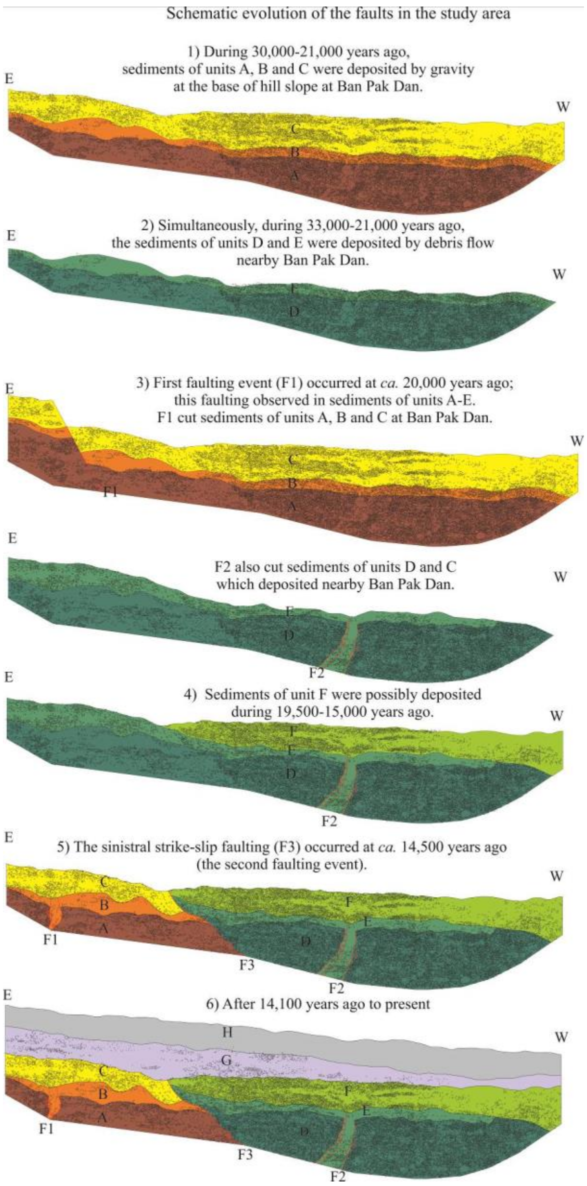

Figure 6. A schematic evolution of the faults in the Ban Pak Dan area, Thub Pud, Phang Nga

6. Recurrence Interval and Slip Rate of the Khlong Marui Fault

We compiled previous trenching data with our results for determining the recurrence interval of seismic events of the Khlong Marui Fault (DMR, 2007; Keawmaungmoon, 2010; Noppradit, 2013; RID, 2009; The Malaysia-Thailand Working Group, 2018). Eight paleoseismological events have been identified along the Khlong Marui Fault; approximate ages of the events are: (1) 20,000 ±1,500 years ago; (2) 14,500 ±1,000 years ago; (3) 12,700 ± 800 years ago; (4) 10,000 ±600 years ago; (5) 8,000 ± 500 years ago; (6) 5,000 ±600 years ago; (7) 3,000 ±600 years ago, and (8) 2,000 ±400 years ago (Figure 7). We observed two seismic events in our trench which are insufficient for determining the recurrence interval of the fault. We infer that the recurrence interval of seismic events on the Khlong Marui Fault from all previous data is between 1,000 and 2,000 years, based on the 2nd – 8th events during late Quaternary. The slip rate on the Khlong Marui Fault can be estimated from

$$\text{Slip rate} = D/R \qquad (2)$$

where D is the slip per event and R is the recurrence interval.

D is of the order of 50 cm (Figure 5), and R is 1,000–2,000 years; therefore, the maximum slip rate is *ca*. 0.25–0.50 mm/yr. These estimates suggest that maximum slip rate on the Khlong Marui Fault, particularly on the Khao Panom segment, is in the range of 0.25–0.50 mm/yr.

7. Discussion

7.1 Multiple ruptures of Quaternary fault in southern Thailand

Dextral motion along the Ranong and the Khlong Marui Faults occurred in late Cretaceous, late Paleocene, and middle Eocene; subsequently, after late Eocene (<37 Ma), the Ranong and the Khlong Marui Faults were reactivated and became sinistral strike-slip faults, as part of a curved belt of sinistral deformation of the Mae Ping and Three Pagoda Faults, which accommodated lateral extrusion during the collision of the Indo-Australian and Eurasian plates and Himalayan orogenesis (Watkinson *et al*., 2011), synchronous

Table 2. Results of OSL dating for quartz concentrates from sediment samples collected in the Ban Pak Dan trench, Thub Pud, Phang Nga, southern Thailand. Remarks: Locations of samples are shown in Figure 5. The single-aliquot regenerative dose (SAR) protocol was applied to measure the paleodose (ED) for each sample. The annual dose (AD) was computed using the concentrations of K, U, Th, and Rb, as shown in the standard table of Bell (1979).

NO.	Sample	Water content	Cosmic ray dose (Gy)	Rb (ppm)	U (ppm)	Th (ppm)	K (%)	AD (Gy/ka)	ED (Gy)	Age (ka)
1	PNA-1	11.31	0.15	85±2.69	1.89±0.07	16.60±0.56	1.55±0.06	2.90±0.21	77.98±2.76	27.00±2.13
2	PNA-2	16.44	0.15	65±2.16	2.08±0.06	17.45±0.48	1.87±0.04	3.10±0.19	85.21±2.20	27.50±1.83
3	PNA-3	14.38	0.15	92±3.38	1.99±0.07	17.37±0.54	1.56±0.05	2.90±0.20	61.82±0.90	21.40±1.50
4	PNA-4	8.85	0.15	97±4.21	1.97±0.06	15.68±0.48	1.75±0.06	3.10±0.20	104.12±1.91	33.60±2.28
5	PNA-5	13.27	0.15	81±2.57	1.95±0.08	17.93±0.65	1.67±0.07	3.04±0.21	65.12±1.09	21.40±1.55
6	PNA-6	13.68	0.15	95±3.34	1.92±0.07	16.26±0.52	1.64±0.06	2.89±0.20	70.55±3.46	24.40±2.08
7	PNA-7	12.09	0.15	84±3.20	1.88±0.06	16.16±0.49	1.79±0.06	3.04±0.20	59.35±2.52	19.50±1.54
8	PNA-8	14.08	0.15	89±3.60	2.20±0.08	19.51±0.63	1.68±0.06	3.18±0.21	44.92±1.87	14.10±1.09

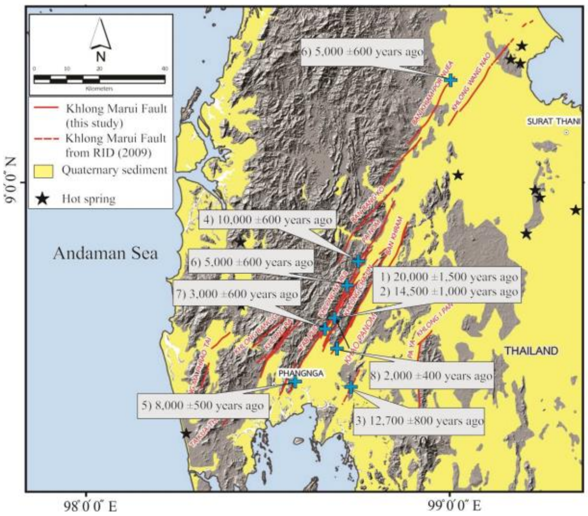

Figure 7. A map of the Khlong Marui Fault showing the interpreted timing of paleoseismological events from paleoseismic trenching data. Note that the dashed red line indicates the segment reported by RID (2009).

with E-W extension in mainland and offshore of Thailand (Hall & Morley, 2004; Nachtergaele *et al*., 2019; Polachan *et al*.,1991). The NE-SW, NW-SE, and N-S trending faults formed during the Quaternary in Thailand are believed to have been activated several times in the Quaternary (Morley *et al*., 2011; Morley & Racey, 2011).

At present, several Quaternary faults are identified as active based on geomorphology, recent earthquakes and paleoseismological data. The Khlong Marui Fault is still active based on these criteria (Charusiri *et al*., 2007; DMR, 2007; Keawmaungmoon, 2010; RID, 2009; The Malaysia-Thailand Working Group, 2018; Thipyopass, 2010). Our study confirms there is evidence of faulting in the late Quaternary. Moreover, other Quaternary faults in southern Thailand located east of the Sumatra-Andaman subduction zone could also be active and generate earthquakes. The Quaternary faults in SE Asia are activated under the present stress field caused by the collision of the Indo-Australian and the Eurasian plates, and multiple ruptures of faults have been reported, for example the Kyaukkyan Fault in Myanmar (Crosetto *et al*., 2018), Sagaing Fault, and the faults in Naka region and Shan Plataea of Myanmar (Tun *et al*., 2014; Wang, Sieh, Tun, Lai, & Myint, 2014). The most important evidence to support the activity of Quaternary faults in southern Thailand, under the N-S compressive stress regime, is microearthquakes generated along the Khlong Marui Fault after the Mw 9.1 Great Sumatra earthquake, detected by seismographs (Bhongsuwan *et al*., 2011; Pispak *et al*., 2010; TMD, 2021).

7.2 Fault activity in southern Thailand

Based on the paleoseismological investigation, the level of activity on the Ranong and the Khlong Marui Faults in southern Thailand appears lower than those of other active faults in northern Thailand, by comparison of recurrence intervals and slip rates (i.e., Quaternary faulting, recurrence interval:1,000 to 2,000 years, and its slip rate is *ca*. 0.25–0.50 mm/yr, see details of active fault's characteristics in northern Thailand in Wiwegwin *et al*. (2014), excepting the Mae Hong Son Fault that shows low activity; this fault is thought to be a spray fault of the Mae Ping Fault. Moreover, in terms of seismicity, the numbers and magnitudes of recorded earthquakes decrease southwards towards Thailand, and stress field emanating from Himalayan Syntaxis may extend down into central plain and the gulf of Thailand (Morley *et al*., 2011). Therefore, from northern to southern regions of Thailand, it is inferred that the activity of active faults progressively diminishes to low levels.

8. Conclusions

We applied remote sensing and aerial photography techniques to a study of the Khlong Marui Fault in Surat Thani and Phang Nga provinces of southern peninsular Thailand. Several fault lines are recognized in the region, trending mainly NE–SW. The main geomorphological features associated with the Khlong Marui Fault are fault scarps, triangular facets, offset streams, shutter ridges, hot springs, and linear valleys. A paleoseismological trench was excavated across the NE–SW Khao Panom segment of the Khlong Marui Fault at Ban Pak Dan to identify faulting events. At least two paleoseismological events with magnitude Mw 6.9 (estimated from the length of the Khao Panom fault segment) and from OSL ages indicating late Quaternary faulting events include 1) 20,000 ±1,500 years ago; and 2) 14,500 ±1,000 years ago. The maximum slip rate is estimated as *ca*. 0.25–0.50 mm/yr. We compiled previous data with this study, and propose that the recurrence interval of seismic events on the Khlong Marui Fault is between 1,000 and 2,000 years. Assessments of Quaternary faults and their behavior are proposed for creating a database supporting seismic hazard assessment in the region.

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References

Bell, W. T. (1979). Thermoluminescence dating: Radiation dose-rate data. *Archaeometry, 21*, 243–245.

Bhongsuwan, T., Pispak, P., & Dürrast, H. (2011). Result of alpha track detection of radon in soil gas in the Khlong Marui fault zone, Southern Thailand: A possible earthquake precursor. *Songklanakarin Journal of Science and Technology, 33*(5), 606–616.

Charusiri, P., Daorerk, V., Archibald, D., Hisada, K., & Ampaiwan, T. (2002). Geotectonic evolution of Thailand: A new synthesis. *Journal of the Geological Society of Thailand, 1*, 1–20.

Charusiri, P., Rhodes, B. P., Saithong, P., Kosuwan, S., Pailoplee, S., Wiwegwin, W., . . . Klaipongpan, S. (2007). Regional tectonic setting and seismicity of Thailand with reference to reservoir construction. *International Conference on Geology of Thailand: Towards Sustainable Development and Sufficiency Economy*, 274–287.

Crosetto, S., Watkinson, I., Min, S., Gori, S., Falcucci, E., & Le Ngal, N. (2018). Evidence of quaternary and recent activity along the Kyaukkyan fault, Myanmar. *Journal of Asian Earth Sciences, 156,* 207-225. doi:10.1016/j.jseaes.2018.01.013

Department of Mineral Resources. (2007). *Investigation on recurrence interval in areas showing trace of movement along the faults in the Prachuabkirikhan, Chumporn, Ranong, Surat Thani, Krabi, Phang Nga and Phuket provinces (Ranong and Klong Marui Faults)* (in Thai). Department of Mineral Resources, Bangkok, Thailand.

Hall, R., & Morley, C. K. (2004). Sundaland Basins. In P. Clift, P. Wang, & W. H. Kuhnt (Eds.), *Continent-Ocean Interactions within the East Asian Marginal Seas: Vol. 149. American Geophysical Union (Geophysical Monograph)* (pp. 55-85). Washington, DC: American Geophysical Union.

Kanjanapayont, P., Klötzli, U., Thöni, M., Grasemann, B., & Edwards, A. M. (2012). Rb–Sr, Sm–Nd, and U–Pb geochronology of the rocks within the Khlong Marui shear zone, southern Thailand. *Journal of Asian Earth Sciences, 56*, 263-275. doi:10.1016/ j.jseaes.2012.05.029

Keawmaungmoon, S. (2010). *Paleoearthquake investigations along the Khlong Marui fault zone, southern Thailand* (Master thesis, Chulalongkorn University, Bangkok, Thailand). Retrieved from http://cuir. car.chula.ac.th/handle/123456789/21243

Lacassin, R., Hinthong, C., Siribhakdi, K., Chauviroj, S., Charoenravat, A., Maluski, H., Leloup, P.H., & Tapponnier, P. (1997). Tertiary diachronic extrusion and deformation of western Indochina: Structure and 40Ar/39Ar evidence from NW Thailand. *Journal of Geophysical Research, 102*(5), 10013–10037.

Morley, C. K., Charusiri, P., & Watkinson, I. K. (2011). Structural geology of Thailand during the Cenozoic. In M. F. Ridd, A. J. Barber, & M. J. Crow (Eds.), *The Geology of Thailand* (pp. 273–334). London, UK: Charlesworth Press.

Morley, C. K., & Racey, A. (2011). Tertiary stratigraphy. In M. F. Ridd, A. J. Barber, & M. J. Crow (Eds.), *The Geology of Thailand* (pp. 223–271). London, UK: Charlesworth Press.

Nachtergaele, S., Glorie, S., Morley, C., Charusiri, P., Kanjanapayont, P., Vermeesch, P., . . . Johan D. G. (2019). Cenozoic tectonic evolution of south-eastern Thailand derived from low-temperature thermo chronology. *Geological Society of London, 177,* 395-411. doi:10.6084/m9.figshare.c.4633064.v1

Noppradit, P. (2013). *Paleoseismological investigations of the Eastern part of the Khlong Marui fault zone in Surat Thani province, Southern Thailand* (Master thesis, Prince of Songkla University, Songkla, Thailand). Retrieved from https://kb.psu.ac.th/psukb/handle/ 2010/9342

Packham, G.H. (1996). Cenozoic SE Asia: reconstructing its aggregation and reorganization. *Geological Society, London, Special Publications, 106*, 123 - 152.

Pailoplee, S., Sugiyama, Y., & Charusiri, P. (2010). Probabilistic seismic hazard analysis in Thailand and adjacent areas by using regional seismic source zones. *Terrestrial, Atmospheric and Oceanic Sciences, 21*, 757-766. doi:10.3319/TAO.2009. 09.21.01(T)

Pailoplee, S. (2014). Earthquake along Klong Marui fault Zone, southern Thailand: Implication from seismicity data. *Bulletin of Earth Sciences of Thailand, 6* (1), 10-17.

Pailoplee, S., & Charusiri, P. (2016) Seismic hazards in Thailand: a compilation and updated probabilistic analysis. *Earth Planet Space, 68*, 98. doi: 10.1186/s40623-016-0465-6

Palasri, C., & Ruangrassamee, A. (2010). Probabilistic seismic hazard map of Thailand. *Journal of Earthquake and Tsunami, 4*, 369-389. doi: 10.1142/S179343111000087X

Pananont, P., Putthapiban, P., Kosuwan, S., Saithong, P., Khaowiset, K., & Charusiri, P. (2010). Paleoseis mology study of the Ranong fault zone in Prachuab Khiri Khan province, south central Thailand. *Advance in Geosciences, 26,* 131-138.

Peltzer, G., & Tapponnier, P. (1988). Formation and evolution of strike-slip fault, rift, and basin during the India-Asia collision: An experimental approach. *Journal of Geophysical Research, 93*(B12), 15,085–15,117. doi: 10.1029/JB093iB12p15085

Pispak, P., Dürrast, H., & Bhongsuwan, T. (2010). Soil-gas radon as a possible earthquake precursor: A case study from the Klong Marui fault zone. *Kasetsart Journal Natural Science, 44*, 1079–1093.

Polachan, S., Pradidtan, S., Tongtaow, C., Janmaha, S., Intarawijitr, K., & Sangsuwan, C. (1991). Development of Cenozoic basins in Thailand. *Marine and Petroleum Geology, 8*, 84–97.

Royal Irrigation Department. (2009). *Active fault investigation of Khlong Lum Rhoe Yai Dam project, Tai Maung, Phang Nga* (in Thai), Royal Irrigation Department Bangkok, Thailand.

Satake, K. (2006). The 2004 Sumatra-Andaman earthquake and Tsunami in the Indian ocean. *Advances in Geosciences, 1*, 1-12.

Searle, M. P., & Morley, C. K. (2011). Tectonic and thermal evolution of Thailand in the regional context of SE Asia. In M. F. Ridd, A. J. Barber, & M. J. Crow (Eds.), *The Geology of Thailand* (pp. 539–571). London, UK: Charlesworth Press.

Shi, X., Wang, Y., Sieh, K., Weldon, R., Feng, L., Chan, C.H., & Liu-Zeng, J. (2018). Fault slip and GPS velocities across the Shan Plateau define a curved southwestward crustal motion around the eastern Himalayan syntaxis. *Journal of Geophysical Research: Solid Earth, 123*, 2502–2518. doi:10. 1002/2017JB015206

Sutiwanich, C., Hanpattanapanich, T., Pailoplee, S., & Charusiri, P. (2012). Probability seismic hazard maps of Southern Thailand. *Songklanakarin Journal of Science and Technology, 34*(4), 453-466.

Thai Meteorological Department. (2006, October 8). Earthquake statistics of Thailand (in Thai). Retrieved from http://www.seismology.tmd.go.th

Thai Meteorological Department (2021, November 11). Earthquake statistics of Thailand (in Thai). Retrieved from http://www.seismology.tmd.go.th

The Malaysia-Thailand Working Group. (2018). *Case study on geological hazard (Active fault) case study 1: Active fault in Bukit Tinggi area, Malaysia, Case study 2: Active fault in Surat Thani area, Thailand.* The annual report of the Malaysia-Thailand Border Joint Geological Survey Committee, Thailand.

Thipyopass, S. (2010). *Paleoearthquake investigation along the Ranong Fault Zone, Southern Thailand* (Master thesis, Chulalongkorn University, Bangkok, Thailand). Retrieved from http://cuir.car.chula.ac.th/ handle/123456789/36462

Tingay, M., Morley, C. K., King, R., Hillis, R., Coblentz, D., & Hall, R. (2010). Present-day stress field of Southeast Asia. *Tectonophysics, 482*, 92-104.

Tun, S.., Wang, Y., Saw, K., Thant, M., Htay, N., Htwe, Y., . . . Sieh, K. (2014). Surface ruptures of the Mw 6.8 March 2011 Tarlay earthquake, Eastern Myanmar. *Bulletin of the Seismological Society of America, 104*, 2915-2932. doi:10.1785/0120130321

United States Geological Survey (2006, November 22). Earthquake Data Base. Retrieved from http://neic.usgs.gov / neis/ epic/ epic global.html.

Wang, Y., Sieh, K., Tun, S. T., Lai, K.-Y., & Myint, T. (2014). Active tectonics and earthquake potential of the Myanmar region. *Journal of Geophysical Research: Solid Earth, 119*, 3767– 3822. doi:10.1002/2013JB010762.

Watkinson, I., Elders, C., Batt, G., Jourdan, F., Hall, R., & Mcnaughton, N. J. (2011). The timing of strike-slip shear along the Ranong and Khlong Marui faults, Thailand. *Journal of Geophysical Research, 116*, 1-26. doi:10.1029/2011jb008379

Watkinson, I., Elders, C., & Hall, R. (2008). The kinematic history of the Khlong Marui and Ranong Faults, southern Thailand. *Journal of Structural Geology, 30*, 1554-1571. doi:10.1016/j.jsg.2008.09.001

Wells, D. L., & Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture area, and surface rupture displacement. *Bulletin of the Seismological Society of America, 84*, 974–1002.

Wiwegwin, W., Hisada, K., Charusiri, P., Kosuwan, S., Pailoplee, S., Saithong, P., . . . Won-in, K. (2014). Paleoearthquake investigations of the Mae Hong Son Fault, Mae Hong Son region, northern Thailand. *Journal of Earthquake and Tsunami, 8*(2), 1450007. doi:10.1142/S1793431114500079

Wiwegwin, W., Kosuwan, S., Weldon, R., Charusiri, P., Xuhua, S., Gavillot, Y., & Gianguo, Z. (2020). Slip rate and recency of large paleoearthquake of sinistral active faults in Indochina region. *17th World Conference on Earthquake Engineering 2020,* 1-12.